Expanding the Kinematics of Jet Measurements

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Two Prongs of Extending Kinematics

Extending Jet Kinematics

Regions Dominated by Background

Regions Requiring More Luminosity

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Regions Requiring More Luminosity

- Pushing to low-p_T
- Pushing to large-R
- Pushing to rare processes

Two Prongs of Extending Kinematics

Extending Jet Kinematics

Regions Dominated by Background

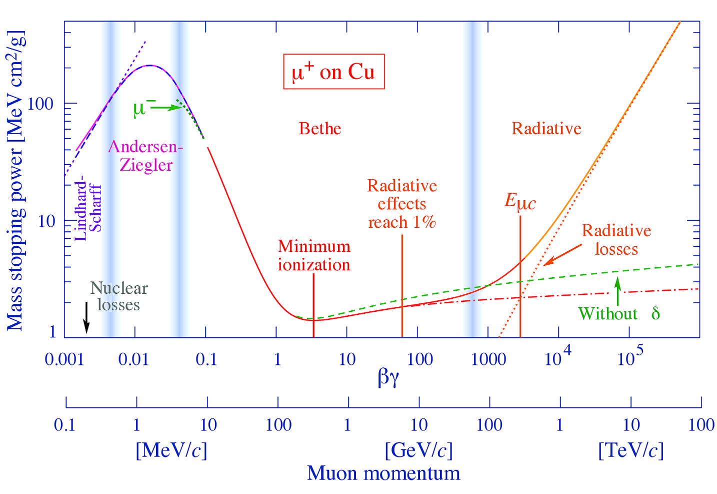
- Pushing to low-p_{T}
- Pushing to large-R
- Pushing to rare processes

Regions Requiring More Luminosity

- Extending to highest-p_{T}
- Extending to forward η
- Extending differential measurements
- Pushing to rare processes

Towards QCD Bethe-Bloch

Via PDG



→ **Goal: Bethe-Bloch for QCD Matter**

Towards QCD Bethe-Bloch

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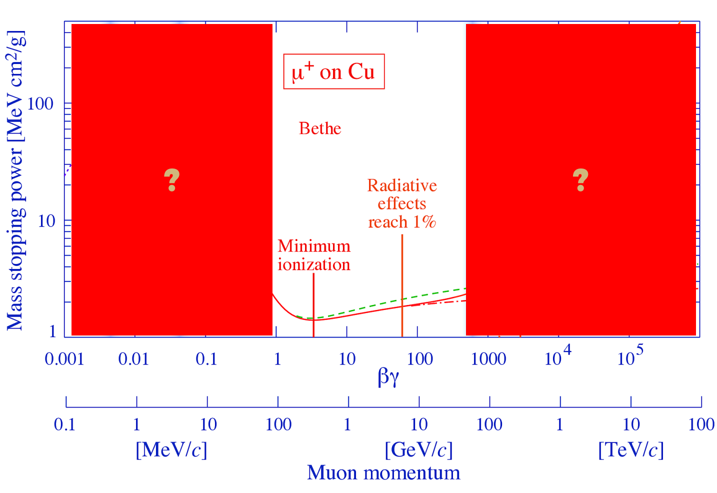
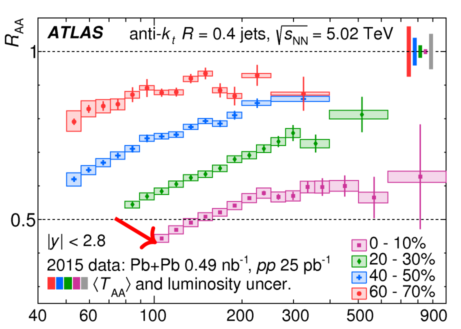


→ **Goal: Bethe-Bloch for QCD Matter**

- **Pushing our kinematic reach may reveal fundamental changes to the jet-medium interactions**

Measurement Defined Limits (I)



PLB 790 (2019) 108

- Top: ATLAS 5.02 TeV R_{AA}, 2015 data
- Each centrality has a different cutoff
  - Reflects the centrality dependent background
- Central events above 100 GeV

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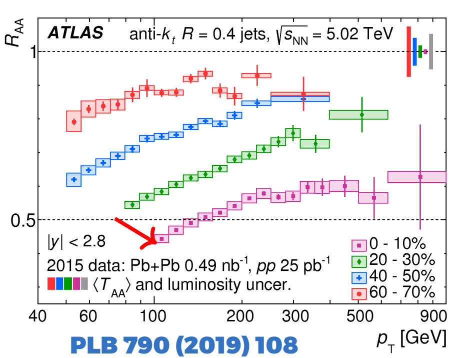

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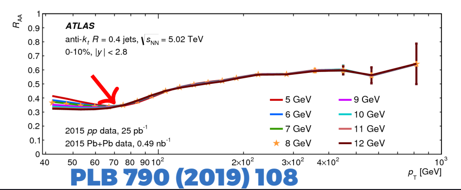
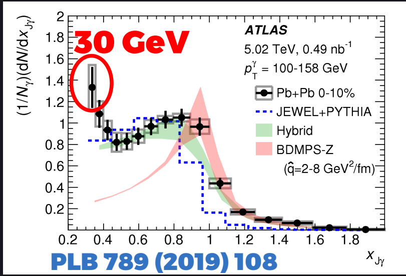


PLB 790 (2019) 108

- **Top: ATLAS 5.02 TeV R_{AA}, 2015 data**
- **Each centrality has a different cutoff**
  - **Reflects the centrality dependent background**
- **Central events above 100 GeV**

- **Bottom: Identifying a region of limited fake jets**
  - **Defined by convergence of track-p_T-in-jets cut**
  - **Giving some room between convergence and measurement**

Measurement Defined Limits (II)



- **Top: ATLAS $x_{J\gamma}$ measurement w/ 2015 data**
  - **Jet p_T extends down to 30 GeV**
  - **Photon-tag changes the fake limitation!**

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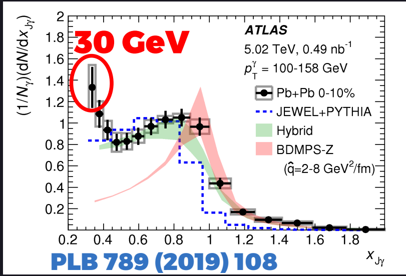
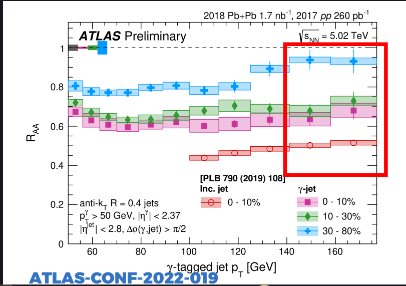


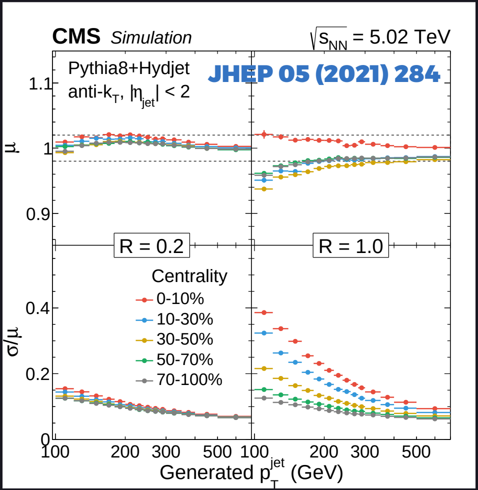


- **Top: ATLAS $x_{J\gamma}$ measurement w/ 2015 data**
  - **Jet p_T extends down to 30 GeV**
  - **Photon-tag changes the fake limitation!**

- **Bottom: ATLAS γ-tagged jet R_{AA} w/ 2018 data**
  - **Conversely, high-p_T extent of the γ-tagged measurement is luminosity limited**
  - **Stat. error visible in all γ-tagged R_{AA} bins**
  - **No visible errors in inclusive jet R_{AA} despite $\sim$1/3 luminosity**

Selected Current Strategies for Studying Jets in Large Backgrouds

CMS Large-R Analysis (I)



- 'Standard' jet reconstruction employing jet-by-jet subtraction
  - Particle-flow constituents
  - Constituent-subtraction method

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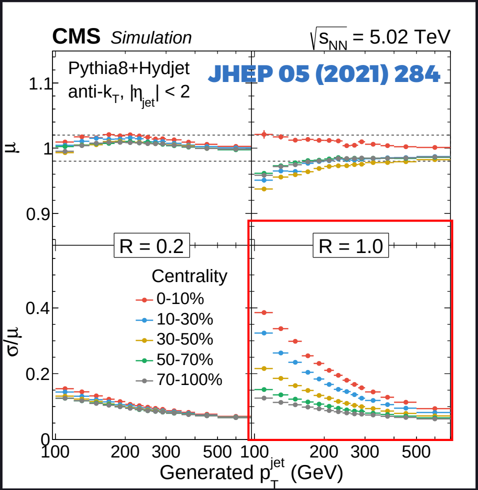
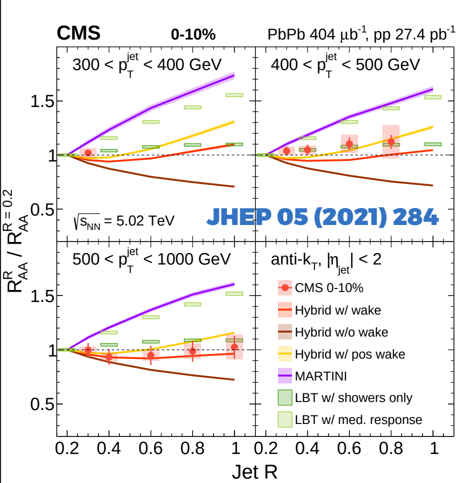


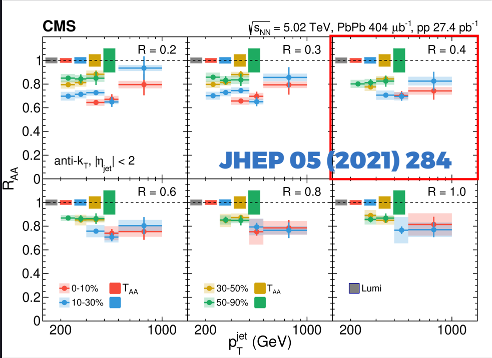
- 'Standard' jet reconstruction employing jet-by-jet subtraction
  - Particle-flow constituents
  - Constituent-subtraction method
- As the R increases, the resolution increases
- To get at the physics of large-R, make a tradeoff
  - Here, restrict to high-p_T

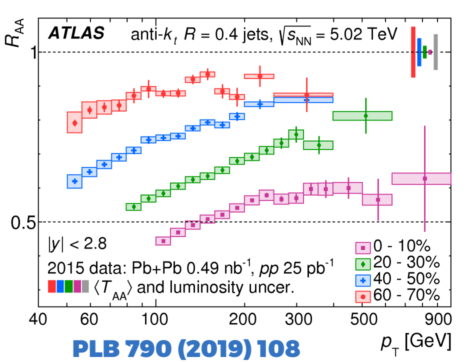
CMS Large-R Analysis (II)



- **Observe a radial dependece of the R_{AA} consistent with 1**
- **The high-p_T restriction represents a significant limitation**
  - **After 2022 Pb+Pb running, $\sim$8x integrated luminosity**
  - **Simultaneously, goal to refine the large-R reco. to push to lower-p_T**

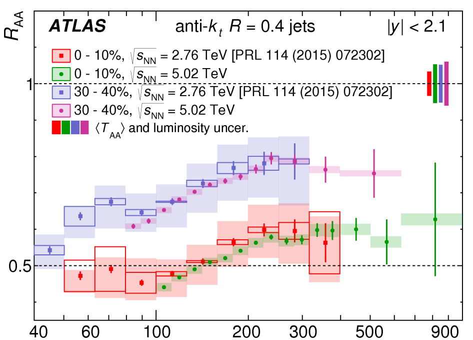
Comparison with ATLAS





- **Region of overlapping R=0.4 0-10% points CMS: ~0.7; ATLAS ~0.6**
- **~15% difference or ~2-3σ**
- **Demands a resolution**
  - **Both experiments working with 2018 data**

A Modest Reframing



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- If experiment was still working with Run 1 systematics, no tension
  - And our lives would be.... dull

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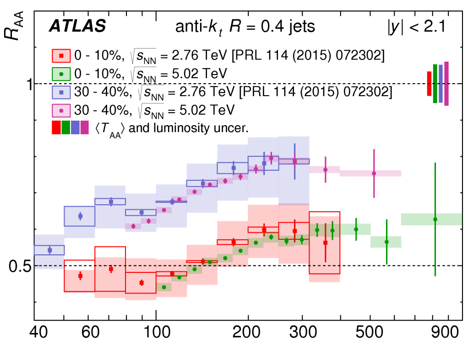

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- Experiments are challenging each other on tight constraints!
  - Reflects years of attacking jet systematic errors

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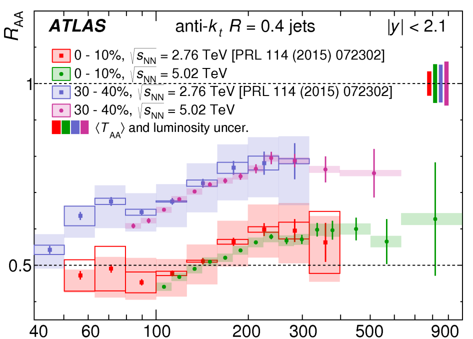

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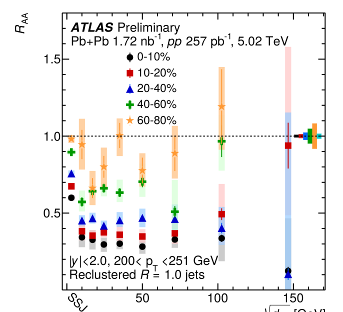
- **If experiment was still working with Run 1 systematics, no tension**
  - **And our lives would be.... dull**
- **Experiments are challenging each other on tight constraints!**
  - **Reflects years of attacking jet systematic errors**
- **With the resolution of this discrepency, the QGP will have nowhere to hide**

ATLAS Large-R Analysis



ATLAS-CONF-2019-056

- ATLAS employs a specialized boot-strap reco.
  - Towers are first clustered into R=0.2 jets
  - This collection is then clustered into R=1.0 jets

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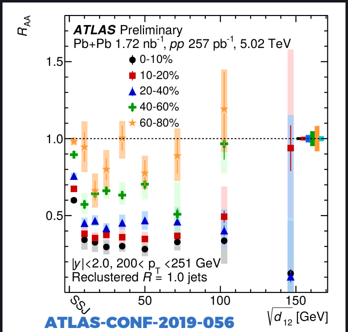

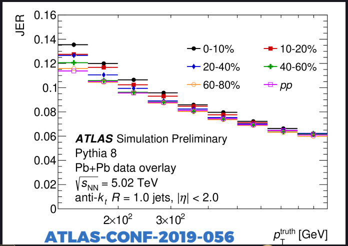

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  - **Towers are first clustered into R=0.2 jets**
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- **Bootstrap reco. differs significantly from standard jets**
  - **Compare the JER to CMS large-R**
    - **Under control to much lower-p_T**
  - **Comes at an interpretive cost**

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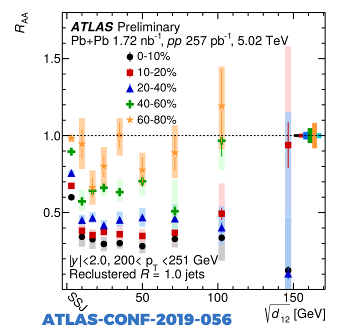

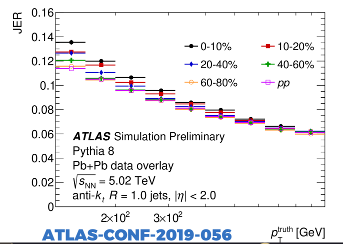

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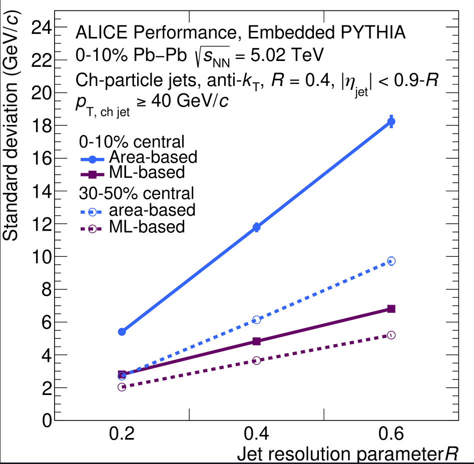
- **Bootstrap reco. differs significantly from standard jets**
  - **Compare the JER to CMS large-R**
    - **Under control to much lower-p_T**
  - **Comes at an interpretive cost**
- **Used to answer a specific physics question**
  - **How does 'pronginess' change quenching?**
  - **Bootstrap reco. is perfect for this question!**

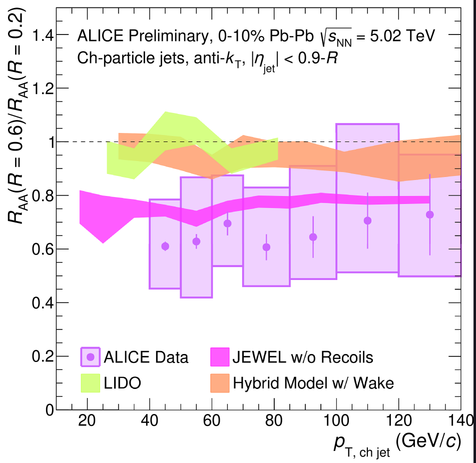
ALICE Large-R Analysis (I)



Via Bossi, QM22

- **Another approach: new tools**
- **Examples:**
  - **Anti-k_T**
  - **Flow modulated UE subtraction**
  - **Constituent subtraction enabling substructure**
- **ALICE employs machine learning to reduce JER**
  - **Shows a nice improvement over area based subtraction**

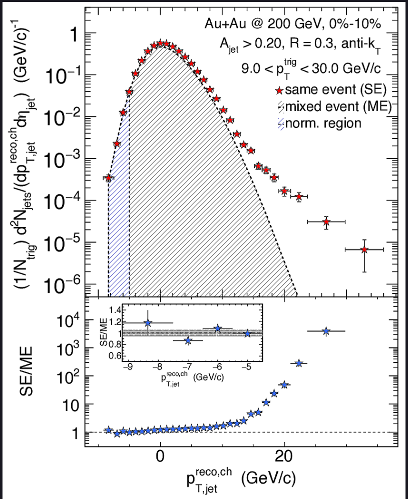
ALICE Large-R Analysis (II)



Via Bossi, QM22

- **Enables extending jet-p_T to far lower than before**
- **Result shows R=0.6/R=0.2 < 1 at low-p_T**
- **Caveat: New tools can behave in unexpected ways**
  - **Not specific to machine learning; merely the nature of being new**
  - **Look forward to more studies/documentation**

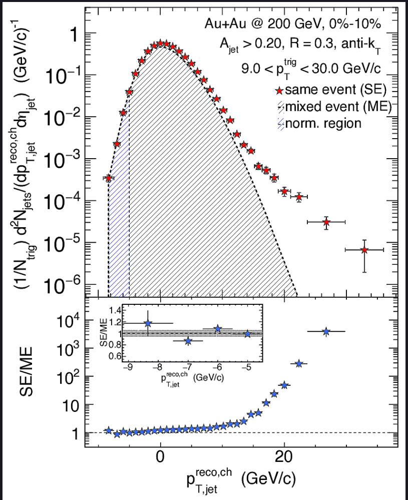
Jet Ensemble Approach



PRC 96, 024905 (2017)

- **Threshold-less jets (i.e. $p_T \to 0$)**
  - **Adopted in some analyses by STAR, ALICE**
  - **Requires extremely precise mixed-event**
- **Addressing a real problem:**
  - **p_T selection on jets is after quenching**
  - **Some physics is lost!**

Jet Ensemble Approach



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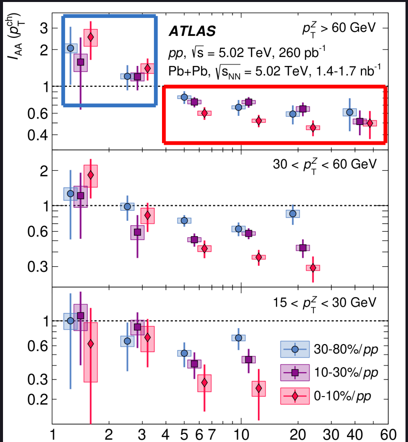
  - Adopted in some analyses by STAR, ALICE
  - Requires extremely precise mixed-event
- Addressing a real problem:
  - p_T selection on jets is after quenching
  - Some physics is lost!
- Some limitations:
  - Calorimeter constituents can be difficult to calibrate in this regime
  - Interpretation of lowest-p_T difficult
- Defer more technical discussion to Peter's talk tomorrow

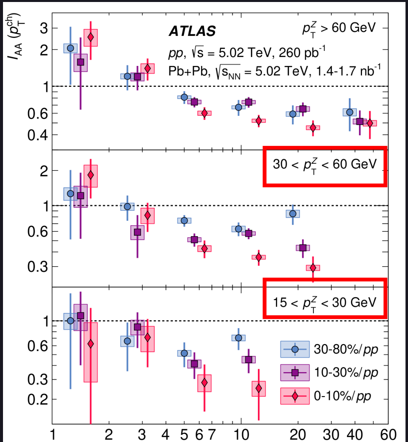
Z+"Jets" w/o Jets (I)



PRL 126 (2021) 072301

- **Left: A Z-tagged measurement by ATLAS of jet fragmentation**
  - **Z p_T sets the scale of hard-scattering**
  - **Study balancing jet fragments**
    - **Defined as remnant after mixed-event subtraction**

Z+"Jets" w/o Jets (I)



PRL 126 (2021) 072301

- **Left: A Z-tagged measurement by ATLAS of jet fragmentation**
  - **Z p_T sets the scale of hard-scattering**
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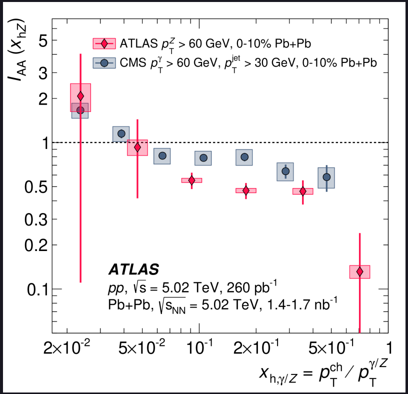
- **NO jet requirement**
  - **An experimental necessity to exploit the kinematic reach of the Z-boson**

Z+"Jets" w/o Jets (II)

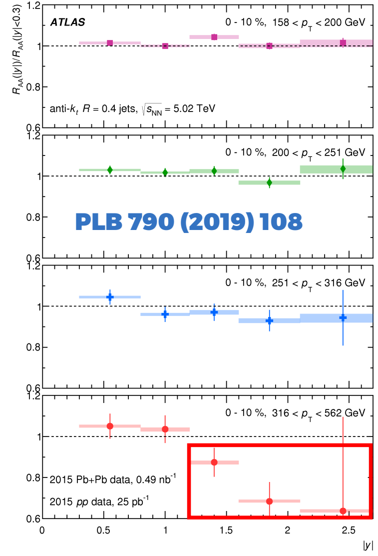


PRL 126 (2021) 072301

- **Z-tagged quenching study w/o jets motivated by experiment**
- **However, removing jet p_T threshold also adds information**
- **Quenched jets excluded by p_T cuts are included in a pure fragment analysis**
  - **Hence modest difference between two measurements on left**
- **Note CMS has a comparable analysis, PRL 128 (2022) 122301**

Prospects of 10nb^{-1} and Alternative Systems

Candidates for Re-analysis 2023



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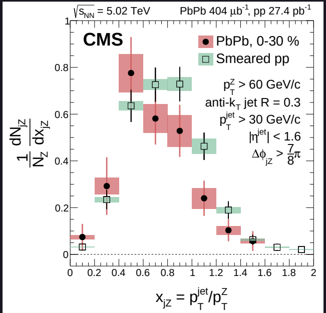


PRL 119 (2017) 082301

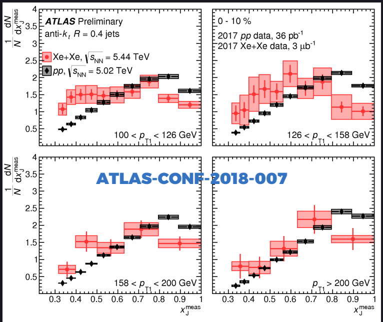
- **2018+2022 Pb+Pb running, expect ∼8x data compared to 2015**
  - **2.4-2.8x improvement in stat. error**
- **Left: 2015 data η differential measurement**
- **Above: 2015 data Z+jets measurement**
- **Also: CMS-style Large R R_{AA}**

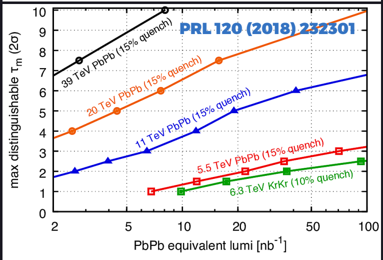
Possible New Measurements

An incomplete list…

- Quenching measurements increasingly differential in substructure
  - ATLAS Large-R style 'prongy' R_{AA}
- Photon-tagged substructure measurements
  - z_g, R_g
  - Remove survival bias
- Hadronic W analysis
  - Necessary component of proposed top measurements
- Multijet configurations
  - More detail shortly…

Alternative Systems at the LHC



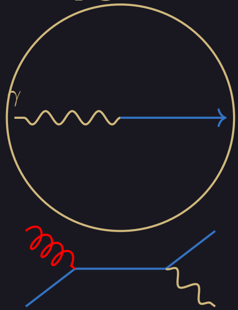


- **Top: ATLAS dijet balance in Xe+Xe**
  - **Part of a successful 8hr pilot run**
- **Bottom: Inspired proposals for HI top production**
- **Of particular interest, Kr+Kr**
  - **Caveat: Expect reduced quenching**
  - **RHIC Cu+Cu suggests we will still observe quenching**
  - **Hadronic W reconstruction easier in reduced background**

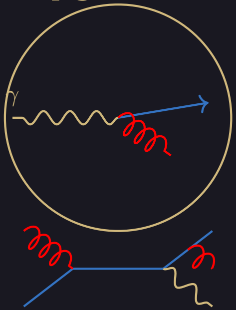
Accessing Higher Order Processes in Background

γ+multijet Observables

As in γ-tagged jet R_{AA} to get at q/g differences

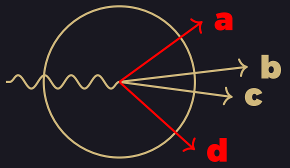


Alternative system to get at q/g differences



- **Challenges:**
  - **Can we construct an observable sensitive to color factor?**
  - **What is the algorithm for multijet mixing?**

Multijet Mixing (I)



Red=Uncorrelated/Fake
Gold=Signal

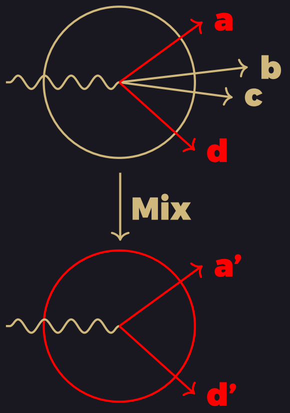
Consider a 'simple' multijet observable

$\vec{x}_{JJ\gamma} = (\mathbf{p}_1 + \mathbf{p}_2)_T \, / \, p_T^{\gamma}$

Do not know a-priori which jets are signal/uncorrelated so construct all pairs

1. Signal
   - b+c
2. Signal with Background
   - a+b
   - a+c
   - b+d
   - c+d
3. Pure Background
   - a+d

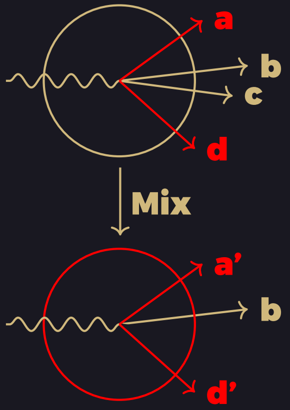
Multijet Mixing (II)



Pure Background can be handled identically to inclusive jet mixing

- Add γ to minimum bias event matched by global parameters, e.g.
  - Centrality
  - Vertex Position
  - Event Plane
- Correlate γ w/ all pairs of jets in-event
- In example, a+d is cancelled by a'+d'

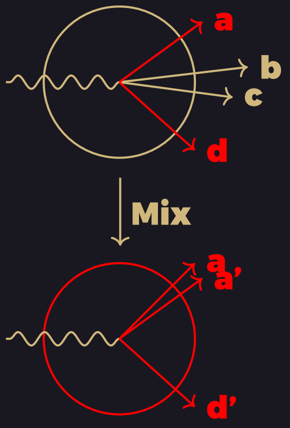
Multijet Mixing (III)



Complications arise in handling Signal+Background contribution

- Mix γ and single jet to minimum bias event
  - Still matched by global parameters
- Correlate γ+jet with all jets from mixed event
- Using our example on the left
  1. b+a' cancels b+a
  2. b+d' cancels b+d
- Mirror result mixing γ+c

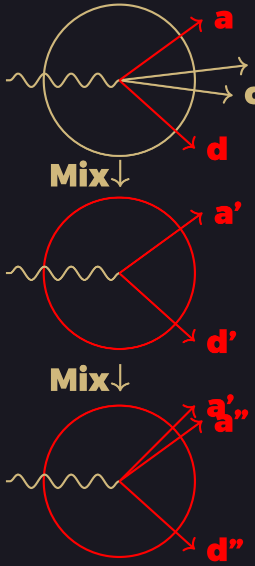
Multijet Mixing (IV)



Previous step leads to overcorrection when accounting for a,d

- **Consequence of not knowing a-priori which jet is signal/uncorrelated**
  - **All must be treated on equal footing**
- **Per example on the left, also get contributions**
  1. **a+a'**
  2. **a+d'**
- **Mirror result for d**

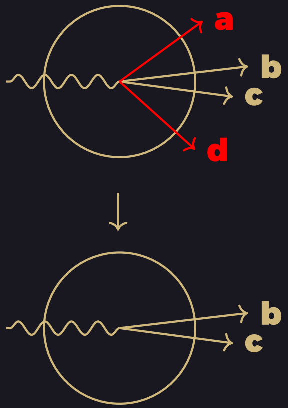
Multijet Mixing (V)



What happened?

- A photon correlated w/ an in-event fake was correlated with a jet from another event
    - The fix is to correct via a double embed
- γ first correlated w/ a',d'
- Then each γ + jet is correlated w/ a'', d''
- Accounts for all contributions detailed on prev. slide

Multijet Mixing (VI)

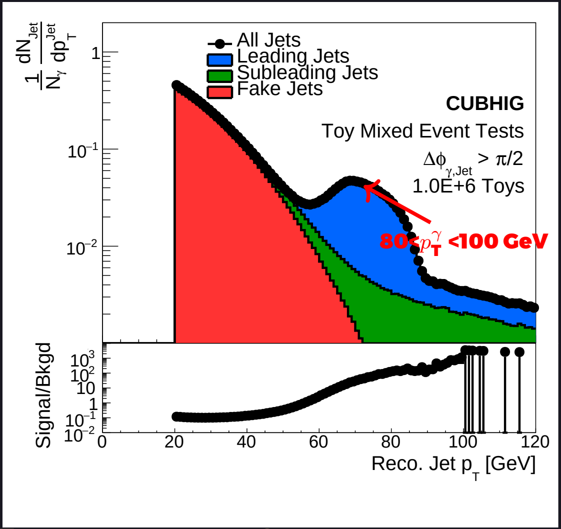


To summarize:

- a+d is removed embedding γ in single event
- b+a, b+d is removed embedding γ+b in single event
- c+a, c+d is removed embedding γ+b in single event
- Double embed corrects for γ+jet in single event where the paired jet is fake

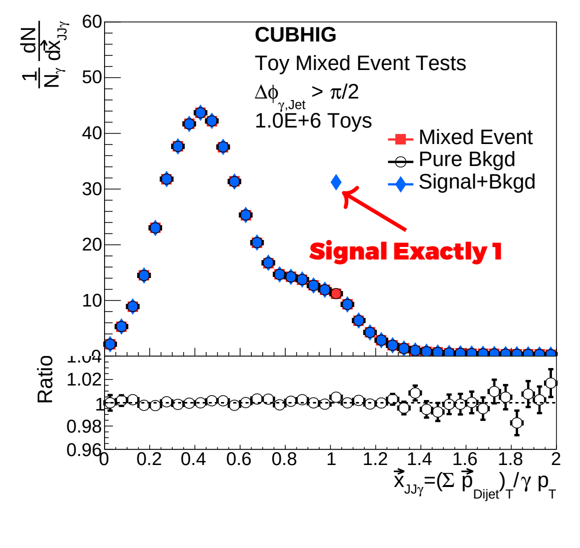
b+c (the physics) remains

Multijet Mixing Toy Demo



- **Randomly generate γ uniform in p_T 80-100 GeV**
- **By construction, make balancing jet-pair equal p_T**
  - **Signal $\vec{x}_{JJ\gamma}$ will always be exactly 1**
- **Split balancing p_T between two jets**
- **Randomly populate with fake jets, dominant at low-p_T**
- **Treating all jets as equivalent, validate multijet mixing**
  - **To be considered a pilot test**

Toy Multijet Closure



- **Able to model the background exactly**
  - **Multijet mixing proof-of-concept**
- **Background is spread across x-axis**
  - **In $x_{J\gamma}$ background is preferentially low $x_{J\gamma}$**
- **Caveat! Toy jets are not extended objects**
  - **Non-zero jet area complicates method**

Conclusion

- **Current kinematic limits are defined by:**
  - **Detector (mostly fixed)**
  - **Reconstruction (we control)**
  - **Observable (we control)**
- **Alt. jet definitions/reco. can answer specific physics questions**
- **New tools have the potential to extend our reach**
  - **As simple as switching to WTA-axis, to more complex machine-learning reconstruction techniques**
- **Increasing integrated luminosity $\rightarrow$ new observables**
  - **Multijet configurations are just one example**
  - **Excited to see many new results soon!**

Thank You!